THERMAL JUDDER ON DRUM BRAKES DUE TO MOUNTED RADIAL RUN OUT

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ABSTRACT - Brake torque variation is a phenomenon which induces seat, steering and body vibration on passenger vehicles these days. One form of the phenomenon is popularly known as brake judder. One root cause of the brake judder is the non-uniform radial thermal expansion of rear brake drums due to localized temperature increase, or known as hot spots. Non-uniform temperature distribution causes ovality which is a deformed oval shape of the circular drum rubbing surface. The ovality is measured as the Mounted Radial Run Out (MRRO) which is the difference between the longest and shortest drum expanding radii. The objective of this paper is to study analytically the generation and reduction of drum MRRO. ABAQUS code is used to analyze the MRRO finite element simulations while ANSA and μETAPOST are used to pre- and post-process simulation results. Explicit heat transient analyses will be selected to correctly predict the phenomenon. Simulation results will be plotted as graphs to illustrate the MRRO and probable deformation scenarios of brake drums. Various design parameters which are significant to reduce MRRO will be outlined. Dynamometer and on-board vehicle tests were conducted to verify the recommendations and benchmark the CAE results.

TECHNICAL PAPER -

1. INTRODUCTION

Frictional contacts between brake linings and rotors/drums will initiate temperature increase to cause thermal deformation. These deformations may induce the generation of disc/drum thickness variation (DTV) which in turn creates localized high temperature areas commonly known as hot spots. Various studies have been conducted to investigate hot spot generation. Experimental and analytical studies by Barber et al. (3) indicated that pressure variations could lead to localized contacts and hot spot generation that is commonly known as thermo elastic instability (TEI). TEI may cause material degradation, thermal cracking and unacceptable brake performance.

Analytical studies on the disk brake temperature prediction due to friction have been conducted as well. Barber et al. (4) studied thermo elastic stability problems and their implications to the design of brakes. Approximate solutions for transient thermo elastic contacts for uniform brake deceleration have been derived and presented. It was observed that depending on the speed of the deceleration, the time to develop hot spots could be different.

Numerically, hot spot investigation is more difficult to undertake. The analysis requires powerful computers and accurate numerical methods to simulate mechanical contacts between fast moving solids. To overcome the need for powerful computers, a combined analytical and numerical computation has been studied by Floquet and Dubourg (5,6). Their work combined fast fourier transform with the finite element method in order to predict transient temperature distribution during braking. The method basically predicted temperature fields on the disk brake and then applied the temperature loads to the rotor finite element model. The method predicted temperature distribution of a moving solid (i.e. the disk brake) under transient heat condition on a physically fixed disc brake finite element model. The temperature loads were then obtained by solving the boundary value problem using the

fast fourier transform technique (FFT). In this process, the thermal and stress analyses were uncoupled and thus, the effects of thermal deformation on the contact, which could affect the heat generation, were not taken into consideration.

To conduct numerical analysis studies on fast moving solids are very challenging and time consuming, requiring the use of high powered computational resources. The computation requires the use of non-linear mechanical approach that simulates non-linear contacts between finite element parts. The fast moving body contacts necessitate the implementation of small incremental iterations in order to guarantee a converged solution and thus, increase computational time considerably.

The scope of this paper is to give a close-up look on the development of brake judder prevention methodologies applied to brake drums. An overview of related brake judder analysis projects, conducted by the author at the Brake CAE and Brake Center of Competence of DaimlerChrysler, will be given. The project spans over a period of ten years which are divided into several stages. The first stage is the development of numerical methodologies to study brake thermal judder phenomena that cause hot spots. The next stage is the development of guidelines to reduce the sensitivity of mounted lateral run out (MLRO) on disc brakes under imbalanced brake bolt torques. The focus of this paper, which is the latest stage of brake judder study, is the development of methodologies to reduce thermal judder due to drum mounted radial run out (MRRO).

Computer simulation techniques derived from ABAQUS applications have been developed since 1997. These techniques implement 3-D brick, hexa finite elements to simulate - more accurately than the tetra or tria elements - frictional contact between discs, drums and their lining pads. The use of fully coupled, simultaneous heat transfer and stress analysis was incorporated. Both implicit and explicit procedures of ABAQUS/Standard and ABAQUS/Explicit were used to solve varieties of brake judder problems (7).

2. HOT SPOT AND THERMAL JUDDER MODELING

Finite element models of a disc brake and two lining pads were developed for this study. The FE models have boundary conditions to simulate fast moving bodies contacting each other. 8-noded solid elements with coupled thermal and stress characteristics were used. Boundary conditions were set up to model the spinning rotor as well as to allow deflection in the axial direction caused by bolt clamping forces. Localized bolt forces produced initial mounted disk run outs on the disk surface. Initial run out could also be generated by the presence of bolt torque variations.

Since the real brake system will undergo thermal and displacement loads simultaneously, coupled temperature-displacement solution was used. In this application, creep and swelling (i.e. structural thermal expansion) response can also be considered. However for our cases, the creep and swelling were negligible since braking only lasts for short period of time.

Four our case studies, the rotor and the pads were modeled realistically with the presence of fins. Thermal film coefficients, defined as the convection rate on certain surfaces, were used as well. The heat convection rates were obtained from the results of computational fluid dynamics (CFD) analyses, after simulating a similar disk brake subjected to certain braking conditions. By using thermal convection rates for the finite element analysis, a link-up between CFD and thermal conduction simulations were developed. The thermal convection rates were difficult to determine or measure.

Realistic braking speed and conditions were also simulated. The brake spinning speed was calculated by taking into account tire and disk brake/rotor radii. The pad pressure loads were applied to the brake by applying the piston into the backing plate of the pads. In turn, the pads clamped the rotor to generate friction. By modifying the pad pressure, several braking

scenarios could be simulated. Constant pad pressures reflected drag braking conditions while variable pad pressure may reflect deceleration, brake fading or snub braking scenarios.

3. CASE STUDIES FOR DISC THERMAL JUDDER

Various case studies were performed for our brake thermal judder models. A model consisting of brake disc and lining assemblies is shown in Figure 1. These models were run to simulate actual disc spinning and braking with a constant speed of 30mph. Correlation runs were conducted to see the accuracy of the temperature increase with dynamometer tests. Figure 2 shows the temperature increase prediction of FEA models with dynamometer results.
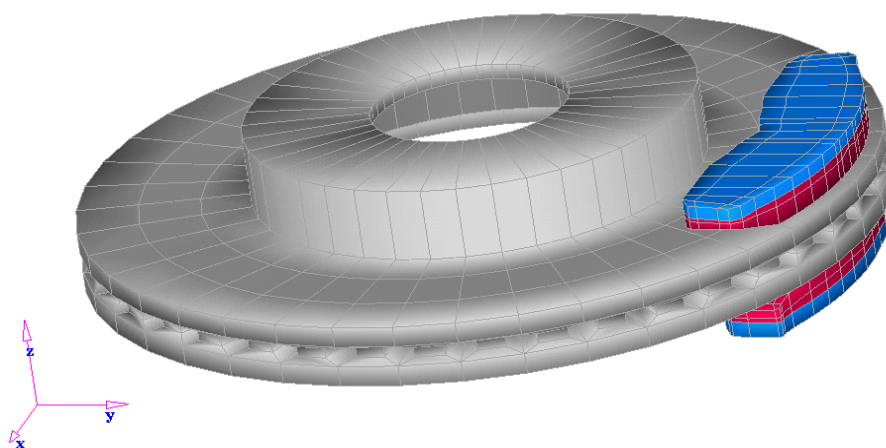

Figure 1. A 15-inch rotor/disc drag braking/correlation study

The following scenarios were applied to the brake model shown in Figure 1. The discs were subjected to a drag braking with constant speed of 60mph for 0.825 sec with a 100psi pad pressure. The lining pad coefficient of friction was 0.34 and the disc initial temperature was 93^OF. The temperature plot after the simulation is shown in Figure 3. As expected, the disc rub track surface does not show any hot spot generation as the disc rub track surface was modeled to be flat and smooth.
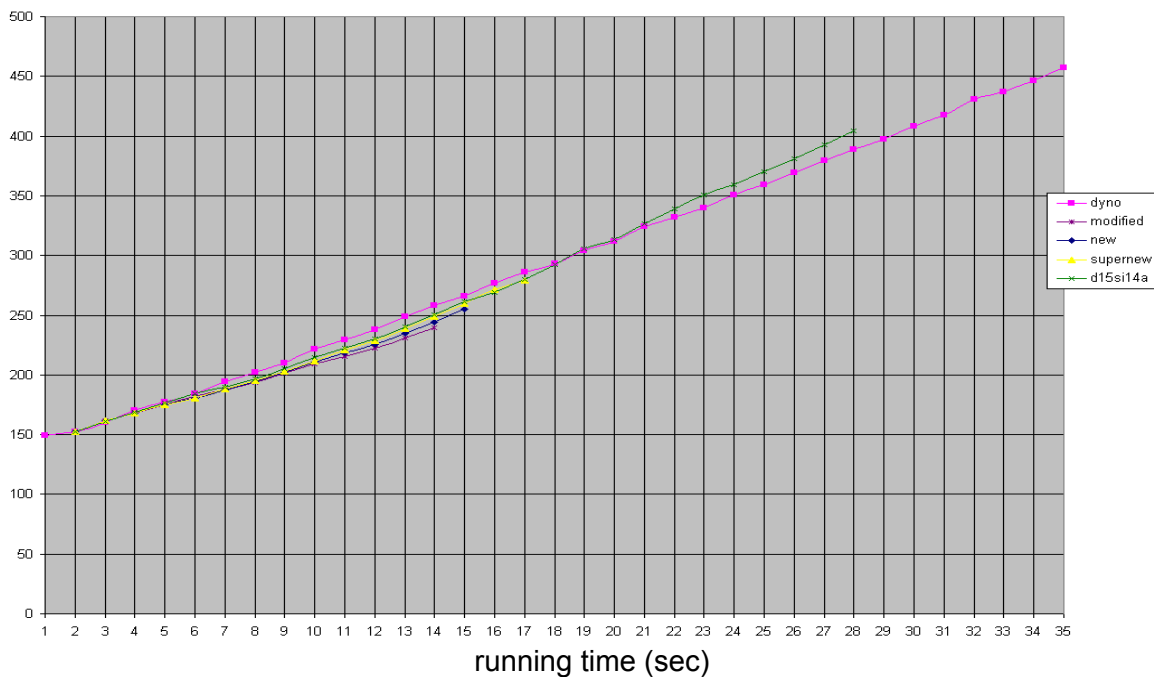
Temperature (^{O}F)

running time (sec)

Figure 2. Correlation Results between FEA Models with Dynamometer Tests
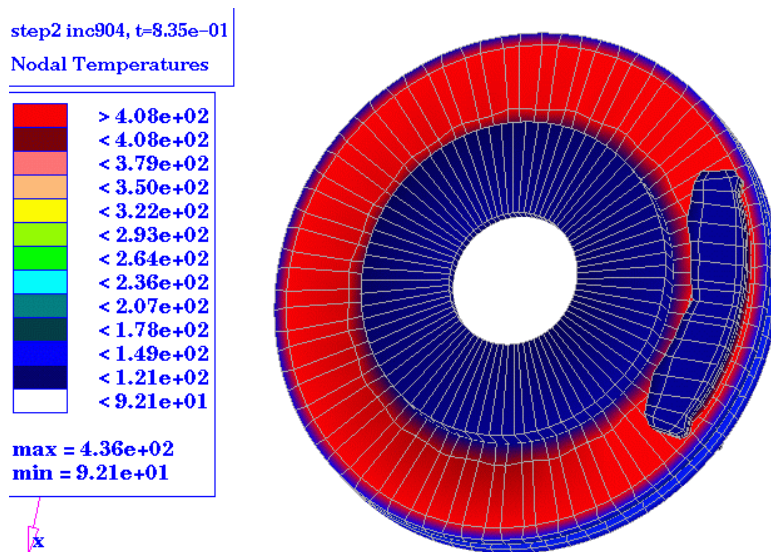

Figure 3. Final Temperature Plot for Smooth Rub Track Surface

To show the presence of DTV, a similar model was modified to include disc thickness variations (DTV) on its rub track. The disc was subjected to a constant drag braking of 60mph speed with less than 100psi lining pad pressure. The following Figure 4 shows the final temperature plot of the disc with hot spots are shown on the disc rub track.
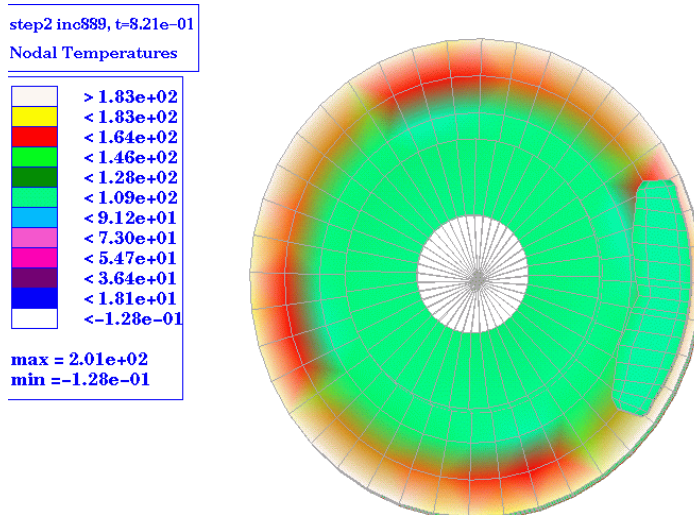

Figure 4. Final Temperature Plot with Hot Spots Shown on the Disc Rub Track

To realistically model brake mounted conditions on vehicles, several runs that showed the presence of imbalanced brake torque were performed. A model that includes a wheel, disc, lining assembly and hub is shown in Figure 5. The model was subjected to bolt torque variation due to un-tightened bolts or imbalance bolt torque. In this case, there were two loose bolts located next to each other. The plot with the presence of hot spot is shown in Figure 6.
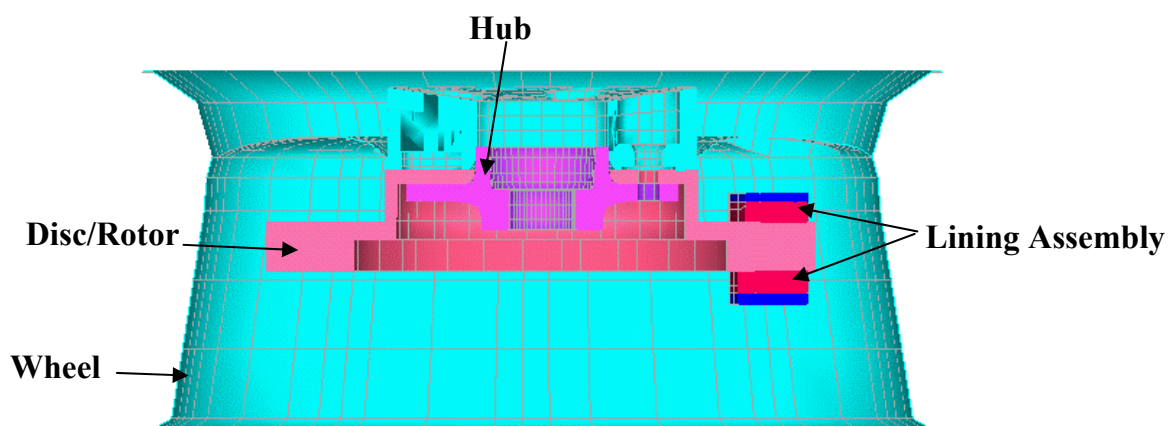

Figure 5. A Wheel, Disc, Hub and Lining Pad Assembly for Hot Spot Modeling
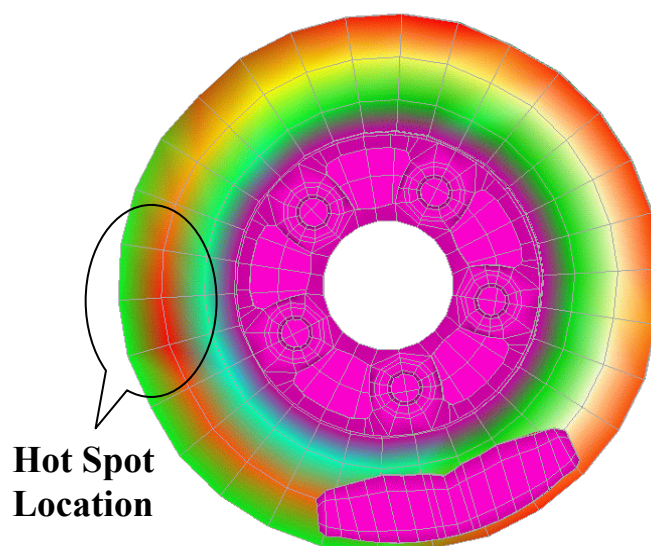
Hot Spot Location

Figure 6. DTV on the Disc Rub Track Showing Hot Spots due to Imbalanced Bolt Torques

In summary, there is a significant correlation between DTV and the generation of hot spots. DTV induces hot spots and the resulting vibration is translated to the driver as the brake pedal pulsation, steering shake, seat or body vibration. Factors that initiate DTV were identified in this study as the initial run out or mounted lateral run out (MLRO) of the disc brake. Lateral run out (LRO) can be triggered by several parameters which are shown in the next stage of our study.

4. MOUNTED LATERAL RUN OUT (MLRO)

In this study (1), a phenomenon - identified as the primary contributor of disc thickness variation (DTV) - was explored. Mounted Lateral Run Out (MLRO) is the main generator of DTV which may cause hot spots and subsequently brake judder. Brake judder is a complex phenomenon in which factors such as, vehicle sensitivity, brake torque variation, caliper slide force, running clearance/rollback, lining material and primarily MLRO sensitivity play significant role in DTV build up which causes brake judder.

A wheel joint configuration, consisting of a wheel, rotor/disc and hub, is shown in Figure 7. When the parts were mounted on a vehicle before wheel lug nuts were tightened, the wheel joint showed no deformations as shown in the figure. Subsequently, once the lug nuts were tightened, the clamping forces exerted on wheel joint parts and especially on the disc would create waviness as shown (as an exaggerated FEA deformation plot) in Figure 8. Mounted Lateral Run Out is measured in m as a distance between the highest to the lowest point of the disc rub track surface or, as can be seen on the plotted graph of Figure 8, as the distance between the crest and the bottom of the curve.
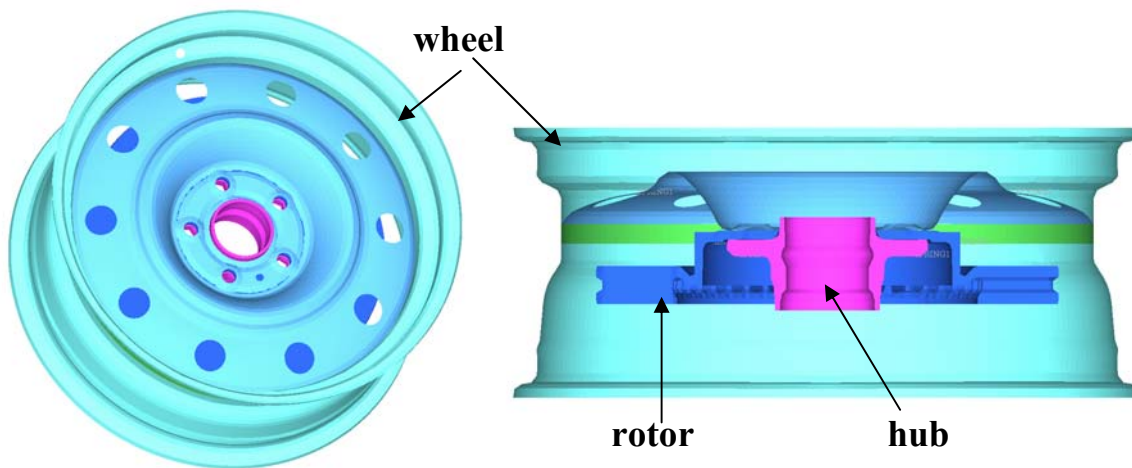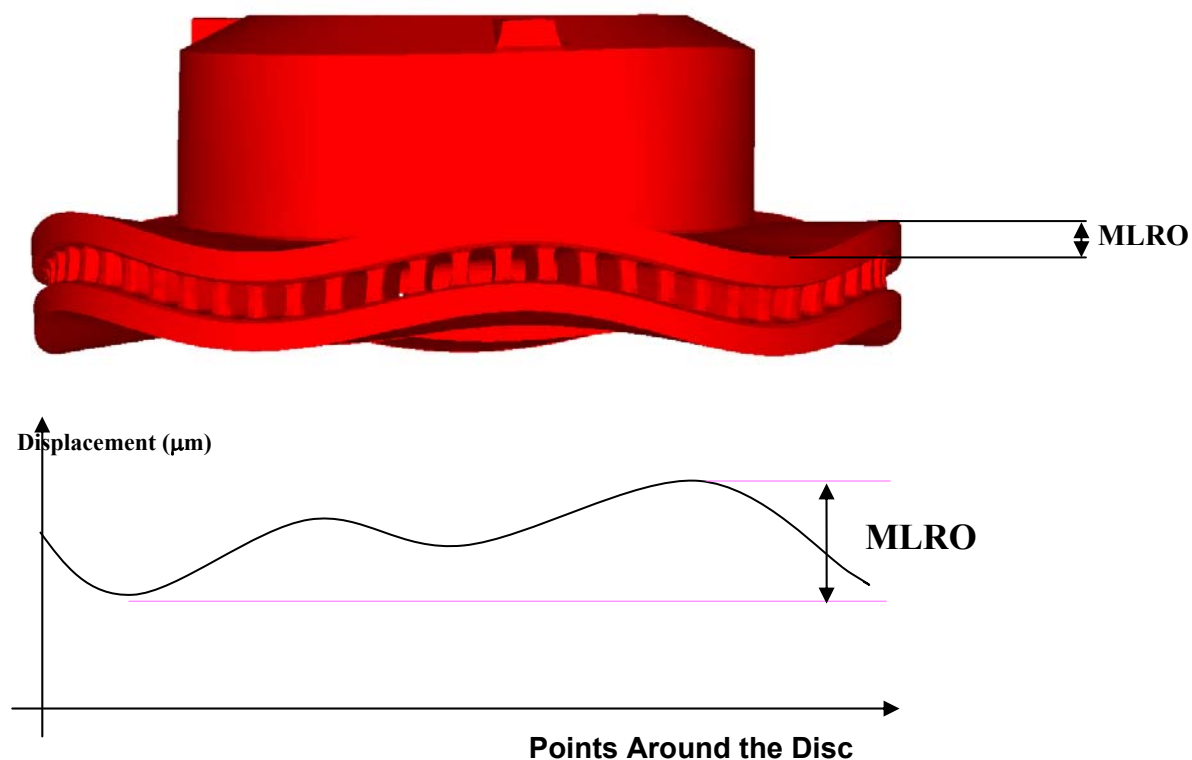
Figure 7. Wheel Joint Configuration

Figure 8. Mounted Lateral Run Out (MLRO) Measurement

Several wheel joint design parameters were investigated to understand their effects to induce MLRO. Wheel step height, wheel mounting pad styles, bearing hub flange thickness, annular groove in the bearing hub flange, wheel to hub flange load path and wheel stiffness were the design parameters identified to be investigated.

A detailed discussion on CAE methods and results of this study can be seen in reference (1). A conclusion was inferred that the most dominant parameters were the wheel step height and the wheel mounting pad styles. Other parameters may still give certain effects on MLRO, however their significance were less dominant than the first two parameters. These design

parameters may be balanced with other performance objectives to give an improved wheel joint overall system characteristic beyond LRO sensitivity.

5. MOUNTED RADIAL RUN OUT (MRRO) ON BRAKE DRUMS

Brake drums, now commonly used as rear brakes (see Figure 9), may experience several performance issues with regards to groan, moan, squeal noise, and roughness/judder. Comprehensive design considerations taking into account the generation of the above performance issues will satisfy the required brake service requirements during brake operational life. In this study, the issue of drum thermal judder due to the roughness on its rub track was investigated. These issues are very common due to the characteristics of a relatively thin rub track sectional width on brake drums (see Figure 10).

To get a clear understanding, drum mounted run outs are measured in the radial direction of the axis or perpendicular to the brake/vehicle axis direction, as shown in Figure 11. It is called the mounted radial run out (MRRO) as compared with the brake disc MLRO. The MRRO is measured as the difference between the deformed maximum (R_{max}) and minimum radii (R_{min}).
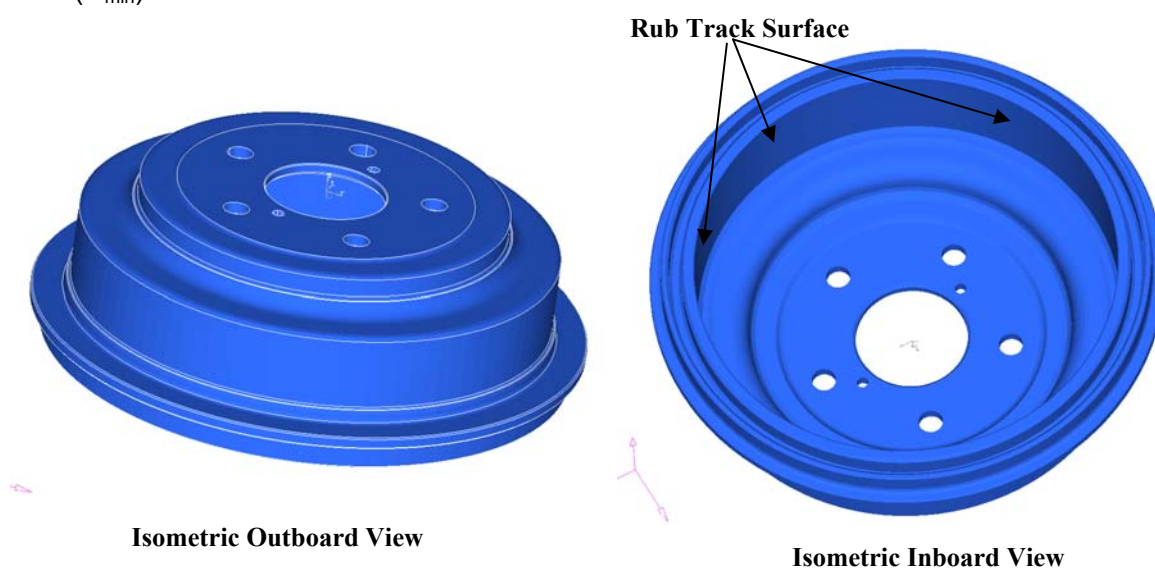
Rub Track Surface

Isometric Outboard View

Isometric Inboard View

Figure 9. Outboard and Inboard Views of Brake Drums

Rub Track Surface

Rub Track Sectional Width (6mm)

Figure 10. Sectional View of a Brake Drum

R_{min}
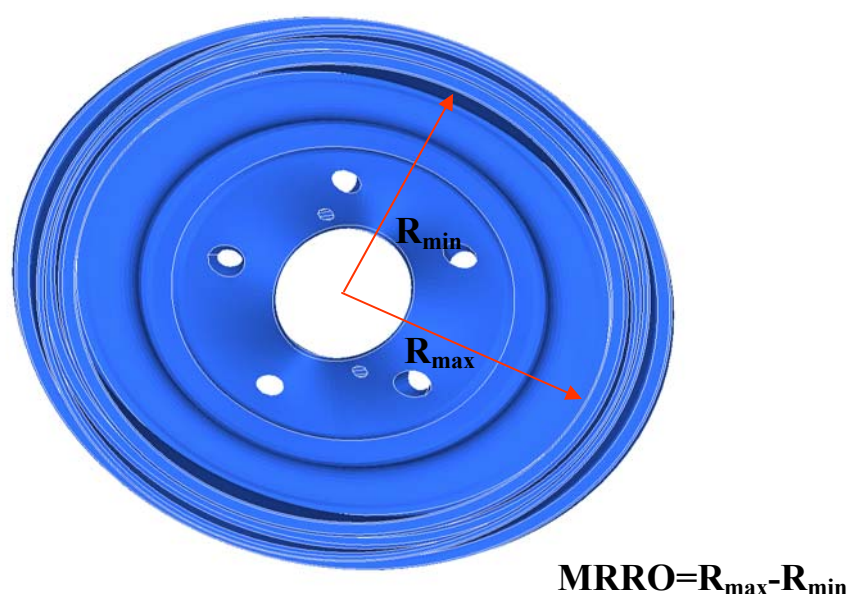
R_{max}

$$MRRO = R_{max} - R_{min}$$

Figure 11. Ovality and Mounted Radial Run Out (MRRO) Measurement

In the case of disc brakes, the lateral run out, i.e. the mounted lateral run out (MLRO) will have to induce disc thickness variation (DTV) before causing hot spots to trigger brake judder. For drum brakes however, uneven temperature increase does not need to cause drum thickness variation (DTV) before causing hot spots and brake judder. The frictional temperature increase can directly cause radial run out and trigger brake roughness/judder.

6. DRUM JUDDER MODELING

The coupled transient temperature and displacement environment in ABAQUS/Explicit (7) was selected for our CAE cases. The consideration was based on the capability to couple stress/displacement and thermal analyses as well as to create efficient runs for our models. Temperature loads were non uniform temperature variations distributed along the drum's rub track section. MRRO's were then measured from the deformed/displaced position of nodal points along the rub track section. Our solutions rely primarily on optimizing brake drum geometrical, dimensional and material properties in order to reduce MRRO's. ANSA and ETAPOST, due to their capabilities to analyze ABAQUS/Explicit problems, were used as the primary pre- and post-processor tools for these applications.

Design Type	Damped Iron (μm)		Gray Iron, 30 (μm)	
	Edge	middle	Edge	middle
Baseline	39.1	22.8	29.98	20.92
Iteration 1	18	11.3	20.23	10.8
Iteration n+1	36.2	17.8	28.3	18.4
Final Design			12.8	6.1

Table 1. MRRO Results of Brake Drum Thermal Judder Analyses

The focus of the study was to reduce MRRO's on both the opening and the middle section of the rub track. Two material properties were considered, damped and gray iron materials.
From Table 1, the baseline designs which create thermal judder issues have relatively unacceptable MRRO values of 29.98 m on the rub track's edge/opening and 20.92 m on the middle of the rub track for gray iron drums. After various iterations, the final design could reduce the edge and middle section MRRO by more than 50%. The edge section MRRO went down to 12.8 m (53% reduction) and the middle MRRO was 6.1 m (71% reduction). The optimized design had a mass increase of 29% over the baseline design. It was the smallest mass increase compared with other design iterations.

7. CORRELATION TESTS

Several brake dynamometer and on-board vehicle tests were conducted by our supplier TRW to verify the CAE findings. The drums with our final design were tested to investigate any reductions or increases in vehicle responses due to judder or torque variation inputs. Dynamometer test results showed 300% lower 2nd order torque variation of the optimized final design drum compared with the baseline/production drums. The 1st order torque variation was also lowered for the final design even though it was not as significant. The final design also showed lower brake accelerations in vertical and fore-aft directions. TRW also conducted on-board vehicle tests to one of the proposed designs and showed significant reduction of steering nibble, vertical seat, vertical axle and fore-aft accelerations.

8. CONCLUDING REMARKS

A review of a ten year project to investigate the generation of thermal judder and its influence to vehicle shake and vibrations was presented. The findings identified that thermal judder on the brake discs and drums were significantly influenced by run outs. For disc brakes, the run out (MLRO) indirectly affects thermal judder through DTV and hot spots generation. For the drum brakes however, the run out induces MRRO directly (without the need to create thickness variation) due to the relatively large oval deformations of the brake drum rub tracks.

Thermal judder is a major contributor to vehicle torque variations which can translate into seat, steering and axle accelerations. A comprehensive design approach should be conducted for vehicle design and engineering to account for the generation and translations of brake judder as well as for the response to the vehicle body or chassis.

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